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13. ABSTRACT (Maximum 200 words)

Our goal is to pursue atom interferometry and advances of the atom laser using Bose-Einstein condensates. Condensates will be moved from a vacuum chamber where they were produced into a science chamber where a great variety of experiments can be carried out without the severe limitations imposed by the cooling and trapping techniques applied in the first chamber. The new chamber has been constructed, and first Bose-Einstein condensates were produced in the spring of 2001. A large-volume optical trap which will be used for translating condensates was successfully tested. In this trap, condensates in lower dimensions and in the upper hyperfine state of sodium were produced. One important element for atom interferometry is the transfer of momentum by simulated light scattering. This scattering can be self-amplified and is accompanied by the amplification of atoms and light. Both processes were studied in detail.



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## **ARO FINAL PROGRESS REPORT**

DURIP grant DAAD19-99-1-0073

“Atom Interferometry, Atom Optics and the Atom Laser”

### **Abstract:**

Our goal is to pursue atom interferometry and advances of the atom laser using Bose-Einstein condensates. Condensates will be moved from a vacuum chamber where they were produced into a science chamber where a great variety of experiments can be carried out without the severe limitations imposed by the cooling and trapping techniques applied in the first chamber.

The new chamber has been constructed, and first Bose-Einstein condensates were produced in the spring of 2001. A large-volume optical trap which will be used for translating condensates was successfully tested. In this trap, condensates in lower dimensions and in the upper hyperfine state of sodium were produced.

One important element for atom interferometry is the transfer of momentum by stimulated light scattering. This scattering can be self-amplified and is accompanied by the amplification of atoms and light. Both processes were studied in detail.

(1) Foreword (optional)

(2) Table of Contents (if report is more than 10 pages)

(3) List of Appendixes, Illustrations and Tables (if applicable)

### **(4) Statement of the problem studied**

To use an optical trap for a Bose-Einstein condensate to transfer the condensate into another vacuum chamber. Ultimately, to perform high precision atom interferometry.

### **(5) Summary of the most important results**

- Successful construction of a new vacuum chamber where BEC was recently achieved.
- Successful test of translating condensates in an optical trap.
- Phase-coherent amplification of atoms and amplification of light in a BEC.
- Realization of Bose-Einstein condensates in lower dimensions.
- Realization of Bose-Einstein condensates of sodium in the upper hyperfine state.

### **(6) Listing of all publications and technical reports supported under this grant or contract. Provide the list with the following breakout, and in standard format showing authors, title, journal, issue, and date.**

(a) Papers published in peer-reviewed journals

W. Ketterle and S. Inouye:

*Does matter wave amplification work for fermions?*

Phys. Rev. Lett., in print; e-print cond-mat/0008232

- S. Inouye, R.F. Löw, S. Gupta, T. Pfau, A. Görlitz, T. L. Gustavson, D. E. Pritchard and W. Ketterle:  
*Amplification of Light and Atoms in a Bose-Einstein Condensate.*  
Phys. Rev. Lett. **85**, 4225-4228 (2000).
- S. Inouye, T. Pfau, S. Gupta, A.P. Chikkatur, A. Görlitz, D.E. Pritchard, and W. Ketterle:  
*Observation of phase-coherent amplification of atomic matter waves.*  
Nature **402**, 641-644 (1999).
- (b) Papers published in non-peer-reviewed journals or in conference proceedings  
W. Ketterle, A.P. Chikkatur, and C. Raman:  
*Collective enhancement and suppression in Bose-Einstein condensates.*  
in: Atomic Physics 17, edited by E. Arimondo, P. DeNatale, and M. Inguscio  
(American Institute of Physics, Melville, New York, 2001), pp. 337-355; e-print  
cond-mat/0010375.
- (c) Papers presented at meetings, but not published in conference proceedings  
A. Görlitz, A.P. Chikkatur, S. Inouye, S. Gupta, T. Pfau, D.M. Stamper-Kurn,  
D.E. Pritchard, and W. Ketterle:  
*Probing and manipulating Bose-Einstein condensates with laser light.*  
16<sup>th</sup> Interdisciplinary Laser Science Conference (ILS-XVI), Providence, RI,  
October 22-26, 2000, Conference Program, p. 96.
- S. Inouye, R. Löw, T. Pfau, S. Gupta, A.P. Chikkatur, A. Görlitz, D.E. Pritchard,  
and W. Ketterle:  
*Amplification of light and atoms in a Bose-Einstein condensate:*  
16<sup>th</sup> Interdisciplinary Laser Science Conference (ILS-XVI), Providence, RI,  
October 22-26, 2000, Conference Program, p. 96.
- W. Ketterle  
*Collective Enhancement and Suppression in Bose-Einstein condensates.*  
2000 Atomic, Molecular and Optical Physics Research Meeting, U.S. Department  
of Energy, Office of Basic Energy Sciences, Warrenton, Virginia, September 26-  
29, 2000, Book of Abstracts.
- T.L. Gustavson, J. Abo-Shaeer, A.P. Chikkatur, A. Görlitz, S. Gupta, Z.  
Hadzibabic, S. Inouye, R. Löw, R. Onofrio, C. Raman, J.M. Vogels, D.E.  
Pritchard, and W. Ketterle:  
*Recent experiments with Bose-Einstein condensates: Amplification of light and  
matter waves, superfluidity, and RF transitions in an optical trap.*  
6<sup>th</sup> Workshop on Atom Optics and Interferometry, Cargese, Corse (France), July  
26-29, 2000, Invited Talks Book of Abstracts.
- S. Gupta, A.P. Chikkatur, A. Görlitz, T.L. Gustavson, S. Inouye, A.E. Leanhardt,  
R. Löw, T. Pfau, T. Rosenband, D.E. Pritchard, and W. Ketterle:  
*Superradiant Rayleigh Scattering, Matter Wave Amplification and Slow Light  
Propagation in a Sodium BEC.*  
6<sup>th</sup> Workshop on Atom Optics and Interferometry, Cargese, Corse (France), July  
26-29, 2000, Book of PosterAbstracts.
- W. Ketterle:  
*New light on Bose-Einstein condensates.*  
ICAP 2000, Florence, June 4-9, 2000, Book of Abstracts, p. 47.

S. Inouye, T. Pfau, R. Loew, S. Gupta, A.P. Chikkatur, A. Görlitz, T. Gustavson, A.E. Leanhard, D.E. Pritchard, and W. Ketterle:  
*Optical and Atom-Optical Properties of a Dressed Bose-Einstein condensate.*

Bull. Am. Phys. Soc. **45**, 109 (2000).

S. Inouye, T. Pfau, S. Gupta, A. Chikkatur, A. Görlitz, D.E. Pritchard, and W. Ketterle:

*Observation of phase-coherent amplification of atomic matter waves.*  
Bull. Am. Phys. Soc. **45**, 48 (2000).

W. Ketterle:

*New Light on Bose-Einstein Condensates.*

Bull. Am. Phys. Soc. **45**, 121 (2000).

W. Ketterle:

*When coherent light interacts with coherent atoms – optical properties of Bose-Einstein condensates.*

Technical Digest, Quantum Electronics and Laser Science Conference (QELS 2000), p. 215.

S. Inouye, T. Pfau, S. Gupta, A. P. Chikkatur, A. Görlitz, D.E. Pritchard, and W. Ketterle:

*Observation of phase coherent amplification of matter waves.*

Technical Digest, Quantum Electronics and Laser Science Conference (QELS 2000), p. 228.

W. Ketterle:

*Bose-Einstein-Kondensation – Quantenmechanik am absoluten Nullpunkt.*

Verhandl. DPG (2000).

A. Görlitz, A. P. Chikkatur, S. Gupta, S. Inouye, T. Pfau, D.M. Stamper-Kurn, D.E. Pritchard, and W. Ketterle:

*Spektroskopie und Manipulation von Bose-Einstein-Kondensaten durch Lichtstreuung.*

Verhandl. DPG (2000).

(d) Manuscripts submitted, but not published

A. Görlitz, J.M. Vogels, A.E. Leanhardt, C. Raman, T.L. Gustavson, J.R. Abo-Shaeer, A.P. Chikkatur, S. Gupta, S. Inouye, T.P. Rosenband, D.E. Pritchard, and W. Ketterle:

*Realization of Bose-Einstein condensates in lower dimensions.*

preprint, cond-mat/0104549.

(e) Technical reports submitted to ARO

**(7) List of all participating scientific personnel showing any advanced degrees earned by them while employed on the project**

Earned degrees:

Dan M. Stamper-Kurn "Peeking and poking at a new quantum fluid: Studies of gaseous Bose-Einstein condensates in magnetic and optical traps", Ph.D. thesis

J.C. Gore "Electronic control of a new apparatus for studying Bose-Einstein condensation", B.S. thesis

Robert Löw "Dressing and trapping Bose-Einstein condensates with light", Diploma Thesis (University of Bonn, Germany)

Involved scientists:

S. Inouye, S. Gupta, T. Rosenband, A.P. Chikkatur, A. Görlitz, T.L. Gustavson, A.E. Leanhardt, D.E. Pritchard, R.F. Löw, T. Pfau, W. Ketterle,

(8) Report of Inventions (by title only)

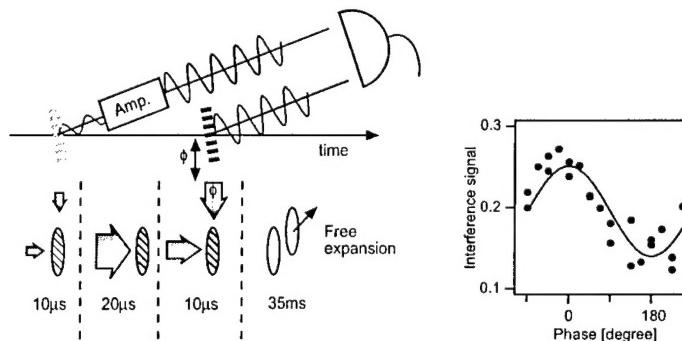
(9) Bibliography

**(10) Appendixes**

More details on the published or submitted work:

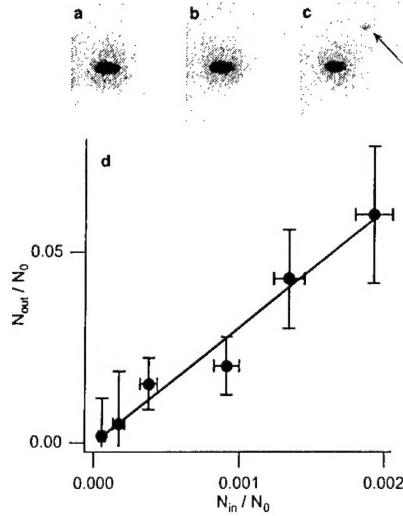
**1. Phase-coherent amplification of matter waves**

Atom amplification differs from light amplification in one important aspect. Since the total number of atoms is conserved (in contrast to photons), the active medium of a matter wave amplifier has to include a reservoir of atoms. One also needs a coupling mechanism which transfers atoms from the reservoir to an input mode while conserving energy and momentum. We have used the matter wave superradiance which we observed in a BEC [1] to realize a matter wave amplifier [2] (see figure).



Experimental scheme for observing phase coherent matter wave amplification. A small-amplitude matter wave was split off the condensate by applying a pulse of two off-resonant laser beams (Bragg pulse). This input matter wave was amplified by passing it through the condensate pumped by a laser beam. The coherence of the amplified wave was verified by observing its interference with a reference matter wave, which was produced by applying a second (reference) Bragg pulse to the condensate. The interference signal was observed after 35 ms of ballistic expansion. The fringes on the right side show the interference between the amplified input and the reference matter wave.

The gain process can be explained in a semiclassical picture. The input matter wave of wave vector  $\mathbf{K}_j$  interferes with the condensate at rest and forms a moving matter wave grating which diffracts the pump light with wave vector  $\mathbf{k}_0$  into the momentum and energy conserving direction  $\mathbf{k}_i = (\mathbf{k}_0 - \mathbf{K}_j)$ . The momentum imparted by the photon scattering is absorbed by the matter wave grating by coherently transferring an atom from the condensate into the recoil mode, which is the input mode. The rate of scattering, which is given by the square of the grating amplitude, is proportional to the number of atoms in the input mode  $N_j$ , implying an exponential growth of  $N_j$  (as long as one can neglect the depletion of the condensate at rest).



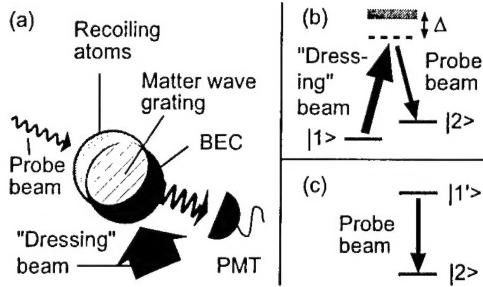
Input-output characteristic of the matter-wave amplifier. (a-c) Typical time-of-flight absorption images demonstrating matter wave amplification. The output of the seeded amplifier (c) is clearly visible, whereas no recoiling atoms are discernible in the case without amplification (a) or amplification without the input (b). The size of the images is 2.8 mm x 2.3 mm. (d) Output of the amplifier as a function of the number of atoms at the input. A straight line fit shows a number gain of 30.

Input matter waves with a well defined momentum were generated by using Bragg scattering to transfer a small part of the condensate into a recoil mode. The input matter wave was amplified by applying an intense radial pump pulse for 20  $\mu$ s. The number of atoms in the recoil mode was then determined by suddenly switching off the trap and observing the ballistically expanding atoms after 35 ms of time-of-flight using resonant absorption imaging. After the expansion, the condensate and the recoiling atoms were fully separated (see figure). Phase-coherence of the matter-wave amplifier was demonstrated with an interferometric technique (see figure).

Our experiment can be regarded as a demonstration of an active atom interferometer. It realizes a two-pulse atom interferometer with phase-coherent amplification in one of the arms. Such active interferometers may be advantageous for precise measurements of phase shifts in highly absorptive media, e.g. for measurements of the index of (matter wave) refraction when a condensate passes through a gas of atoms or molecules [3]. Since the most accurate optical gyroscopes are active interferometers [4], atom amplification might also play a role in future matter-wave gyroscopes [5]. In an independent effort a group at the University of Tokyo [6] has achieved similar results on the amplification of matter waves.

## 2. Amplification of light and atoms in a Bose-Einstein condensate

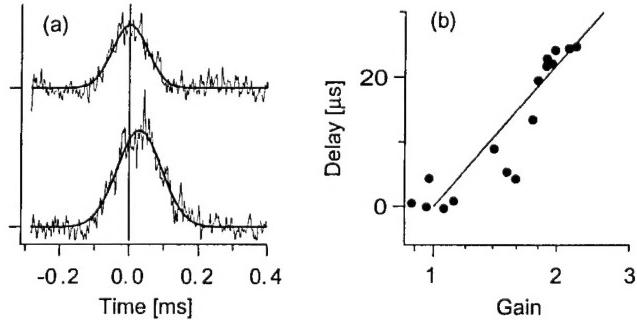
Bose-Einstein condensates illuminated by an off-resonant laser beam (“dressed condensates”) were used to realize phase-coherent amplification of matter waves [2, 6]. The amplification process involved the scattering of a condensate atom and a laser photon into an atom in a recoil mode and a scattered photon. This four-wave mixing process between two electromagnetic fields and two Schrödinger fields became a self-amplifying process above a threshold laser intensity, leading to matter wave gain. However, the symmetry between light and atoms indicates that a dressed condensate should not only amplify injected atoms, but also injected light.



Amplification of light and atoms by off-resonant light scattering. (a) The fundamental process is the absorption of a photon from the “dressing” beam by an atom in the condensate (state  $|1\rangle$ ), which is transferred to a recoil state (state  $|2\rangle$ ) by emitting a photon into the probe field. The intensity in the probe light field was monitored by a photomultiplier. (b) The two-photon Raman-type transition between two motional states ( $|1\rangle$ ,  $|2\rangle$ ) gives rise to a narrow resonance. (c) The dressed condensate is the upper state ( $|1'\rangle$ ) of a two-level system, and decays to the lower state (recoil state of atoms,  $|2\rangle$ ) by emitting a photon. Since the system is fully inverted, there is gain for the probe beam.

We have studied the optical properties of a dressed condensate above and below the threshold for the matter wave amplification [7]. The optical gain below the threshold has a narrow bandwidth due to the long coherence time of a condensate. The gain represents the imaginary part of the complex index of refraction. A sharp peak in the gain implies a steep dispersive shape for the real part of the index of refraction  $n(\omega)$ . This resulted in an extremely slow group velocity for the amplified light. The figure shows that light pulses were delayed by about 20  $\mu\text{s}$  across the 20  $\mu\text{m}$  wide condensate corresponding to a group velocity of 1 m/s. This is one order of magnitude slower than any value reported previously [8].

Above the threshold to matter wave amplification, we observed non-linear optical behavior. Thus we could map out the transition from single-atom gain to collective gain.



Pulse delay due to light amplification. (a) Amplification and 20  $\mu\text{s}$  delay were observed when a Gaussian probe pulse of about 140  $\mu\text{s}$  width and 0.11  $\text{mW/cm}^2$  peak intensity was sent through the dressed condensate (bottom trace). The top trace is a reference taken without the dressed condensate. Solid curves are Gaussian fits to guide the eyes. (b) The observed delay time was proportional to  $\ln(g)$ , where  $g$  is the observed gain.

### 3. Does matter wave amplification work for fermions?

Several recently observed phenomena Bose-Einstein condensates, superradiance of atoms, four-wave mixing and matter wave amplification were described as processes which are bosonically stimulated, i.e., their rates are proportional to  $(N+1)$ , where  $N$  is

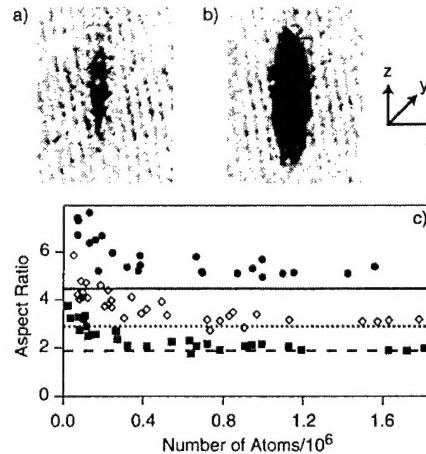
the number of identical bosons in the final state. However, we had pointed out that atomic superradiance does not depend on Bose-Einstein statistics and would occur for thermal atoms or even for fermions, although with a much shorter coherence time [1]. These suggestions have stirred a controversy among researchers.

In Ref. [9], we reconciled the different physical descriptions with the central result that the stimulated processes mentioned above do not rely on quantum statistics, but rather on symmetry and coherence. Bosonic quantum-degeneracy is sufficient, but not necessary for these processes. It represents only one special way to prepare a system in a cooperative state which shows coherent and collective behavior.

#### **4. Realization of Bose-Einstein condensates in lower dimensions**

Bose-Einstein condensates of sodium atoms have been prepared in optical and magnetic traps in which the energy-level spacing in one or two dimensions exceeds the interaction energy between atoms. This realized condensates of lower dimensionality [10]. In anisotropic traps, a primary indicator of crossing the transition temperature for Bose-Einstein condensation is a sudden change of the aspect ratio of the ballistically expanding cloud. The transition to lower dimensions is a smooth cross-over, but has similar indicators. In the 3D Thomas-Fermi limit the degree of anisotropy of a BEC is independent of the number  $N$  of atoms, whereas in 1D and 2D, the aspect ratio depends on  $N$ . This was used in our experiments as a distinctive feature of lower dimensionality.

In our traps, the ratio of the highest to lowest frequency was about 100. Due to this extreme geometry the number of atoms at the cross-over to lower-dimensionality was rather large ( $> 10^5$  in the 2D case) which provides a good starting point for the exploration of phenomena which only occur in one or two dimensions.



Cross-over from 3D to 2D condensates observed in the change of the aspect ratio. Condensates were released from a disk-shaped optical trap and observed after 15 ms time-of-flight. a) (2D) condensate with  $9 \times 10^4$  atoms b) (3D) condensate with  $8 \times 10^5$  atoms in a trap with vertical trap frequency of 790 Hz. c) Aspect ratio as a function of atom number for optical traps with vertical trap frequencies of 1620 Hz (filled circles), 790 Hz (open diamonds) and 450 Hz (filled squares). The lines indicate the aspect ratios as expected for condensates in the 3D (Thomas-Fermi) regime. We attribute discrepancies between expected and measured aspect ratio for large numbers to the influence of anharmonicities on the measurement of the trap frequencies.

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3. J. Schmiedmayer, M.S. Chapman, C.R. Ekstrom, T.D. Hammond, S. Wehinger, and D.E. Pritchard, *Phys. Rev. Lett.* **74**, 1043 (1995).
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5. T.L. Gustavson, P. Bouyer, and M.A. Kasevich, *Phys. Rev. Lett.* **78**, 2046 (1997).
6. M. Kozuma, Y. Suzuki, Y. Torii, T. Sugiura, T. Kuga, E.W. Hagley, and L. Deng, *Science* **286**, 2309 (1999).
7. S. Inouye, R.F. Löw, S. Gupta, T. Pfau, A. Görlitz, T.L. Gustavson, D.E. Pritchard, and W. Ketterle, *Phys. Rev. Lett.* **85**, 4225 (2000).
8. L.V. Hau, S.E. Harris, Z. Dutton, and C.H. Behroozi, *Nature* **397**, 594 (1999).
9. W. Ketterle and S. Inouye, *Phys. Rev. Lett.* **86**, 4203 (2001).
10. A. Görlitz *et al.*, preprint, cond-mat/0104549.

Final Report: DAAD19-99-2109 (OSP 6816300)

Equipment Listing:

In May of 1999, Prof. Ketterle requested prior approval from ARO through ONR Boston, to transform this entire project into one equipment fabrication. The entire budget was used to fabricate a new vacuum chamber and atom trap with accessories. The bulk of the funding (\$105K) was expended on purchase of materials and services, i.e. optics, electronics and vacuum parts.

These are the actual equipment items that were purchased:

1. Dycor LC 100m MASS spectrometer, Ametek \$5750
2. Motorized linear Stage 400mm, Phytron, \$5810